

Sept. 28, 1965

M. PRATS

3,208,516

CONTROL METHOD IN UNDERGROUND COMBUSTION DRIVES

Filed May 13, 1963

3 Sheets-Sheet 1

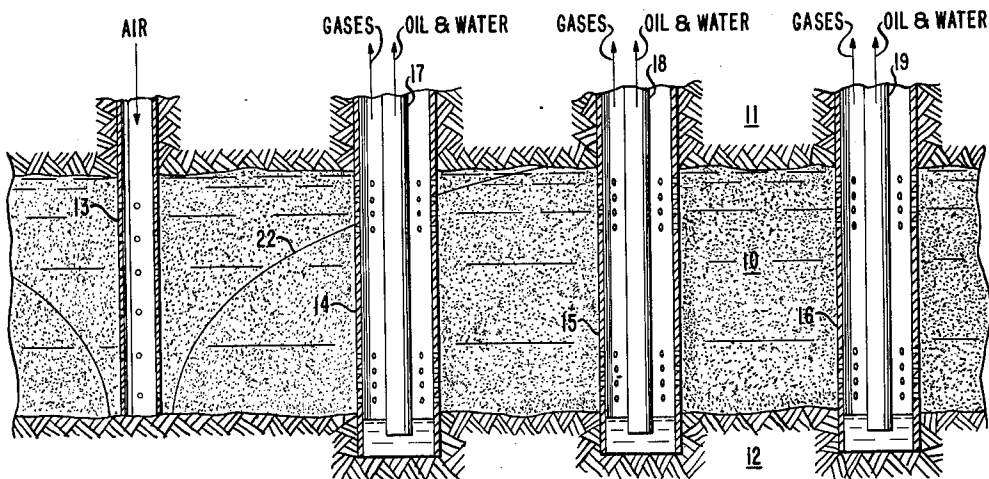


FIG. 1

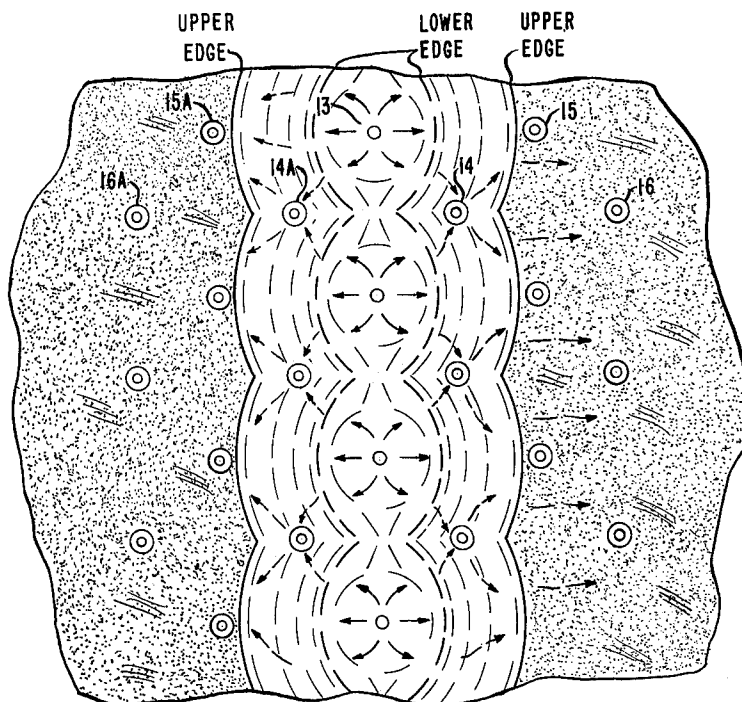


FIG. 2

INVENTOR:  
MICHAEL PRATS  
BY: *John R. Williams*  
HIS ATTORNEY

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M. PRATS

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3 Sheets-Sheet 2

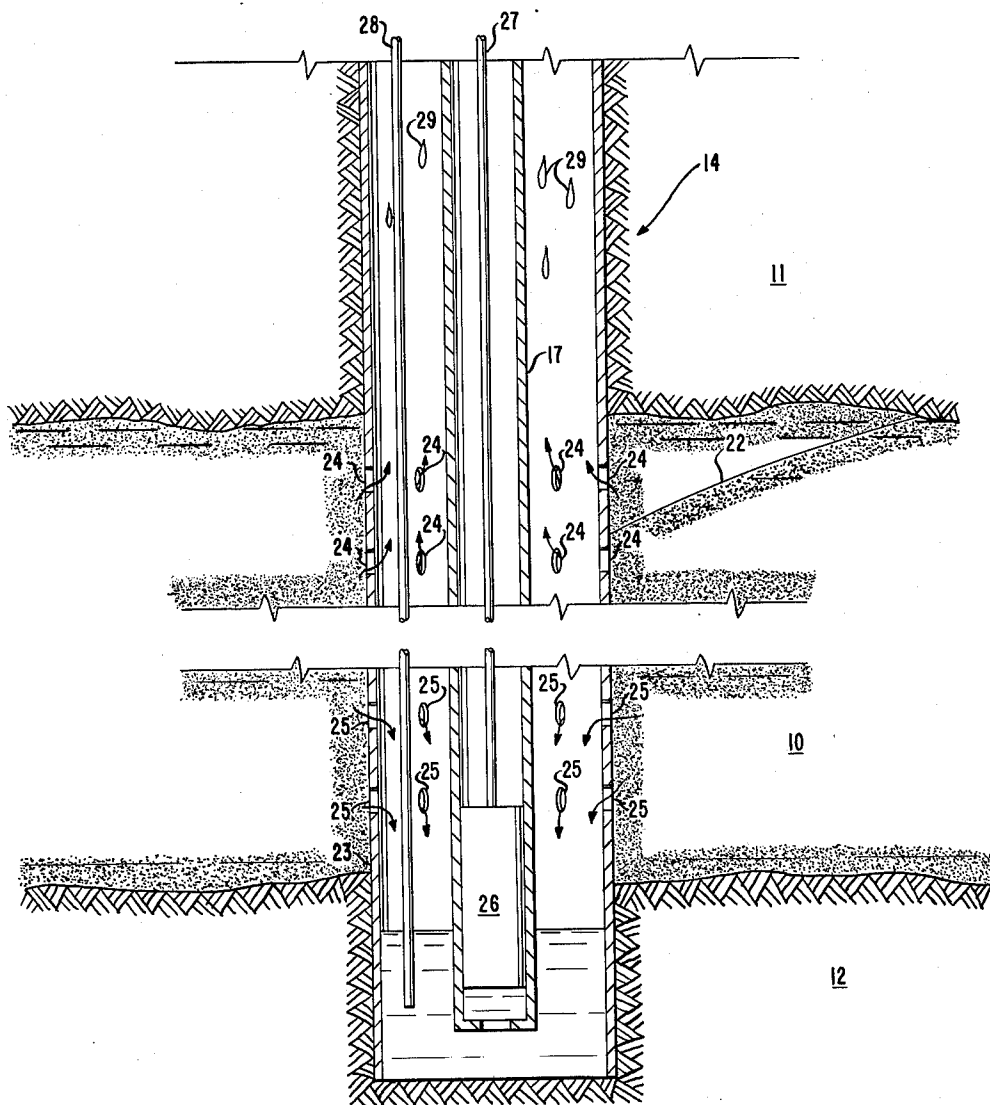


FIG. 3

INVENTOR:

MICHAEL PRATS

BY: *John K. Williams*  
HIS ATTORNEY

Sept. 28, 1965

M. PRATS

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3 Sheets-Sheet 3

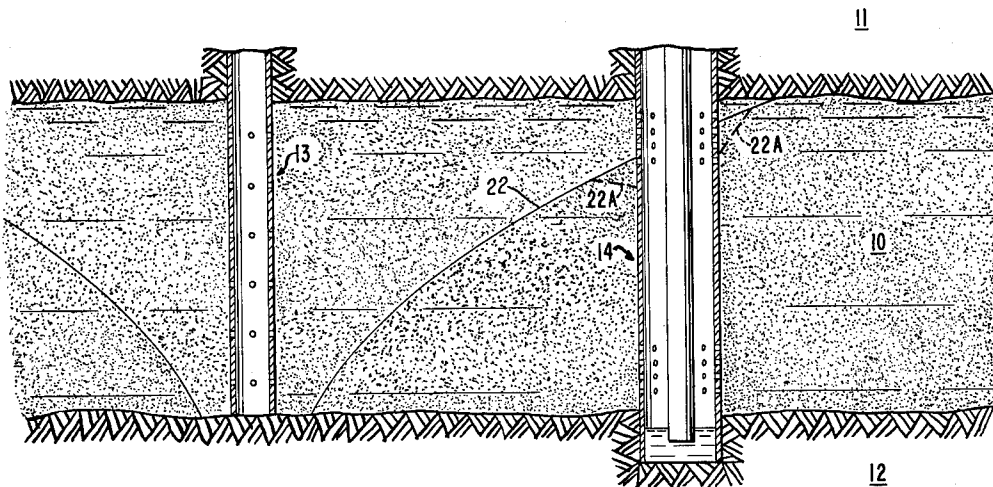


FIG. 4

INVENTOR:

MICHAEL PRATS

BY: *John K. Ulfema*  
HIS ATTORNEY

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3,208,516

## CONTROL METHOD IN UNDERGROUND COMBUSTION DRIVES

Michael Prats, Houston, Tex., assignor to Shell Oil Company, New York, N.Y., a corporation of Delaware  
Filed May 13, 1963, Ser. No. 279,903  
3 Claims. (Cl. 166-4)

The present invention relates to an underground combustion drive process in which substantially all of the injected combustion-supporting gas is utilized to generate heat within the producing reservoir. More particularly, the invention is directed to a process for using an inclined combustion front to maximize the effectiveness of an underground combustion drive. In a specific aspect, the invention comprises a process wherein combustion-supporting gases introduced into a producing reservoir are effectively utilized by restricting the amount of unreacted combustion-supporting gas that is produced from the formation with the effluent hydrocarbons removed therefrom.

Generally, when using in-situ combustion in a producing hydrocarbon formation to facilitate production therefrom, it is assumed that the combustion front will be vertical. Previous theory suggests that a combustion front initiated at a well within a producing formation will move away from the well while maintaining a relatively vertical configuration. In an in-situ combustion process, substantially all of the combustion-supporting gas (e.g., oxygen) is reacted at the front before it can pass through the producing formation to production wells located downstream relative to the flow of fluids through the reservoir formation. A vertical combustion front has the disadvantage that its surface area is bounded by the vertical thickness of the producing formation or reservoir in which it is being used. This limited surface area is a disadvantage since the zone of the formation heated by the combustion front is limited to a relatively narrow band that moves through the formation at the rate of growth of a gas bubble filling all of the pore space between the combustion front and the injection well.

It is noted that the combustion-supporting gasses supplied to in-situ combustion fronts perform a driving function as well as a combustion-supporting function. More specifically, as the combustion-supporting gas is reacted at the combustion front the heat produced lowers the viscosity of hydrocarbons within the formation and the drag forces exerted by the flow of the injected gas function to force these less viscous hydrocarbons to production wells downstream from the injection well. However, with a vertical combustion front the heating of the formation tends to be confined to the region of a vertical wall that slowly advances through the formation. The hydrocarbons reduced in viscosity by the heating tend to cool with in the producing formation prior to the time they reach the production wells. Upon cooling, the hydrocarbons form a heavy viscous bank which impedes the flow of combustion-supporting gas and may reduce its flow to a rate insufficient to sustain the combustion. When the combustion front dies, the secondary recovery process is rendered ineffective.

The aforementioned difficulties encountered with the use of an in-situ combustion process having a vertical combustion front do not, however, always occur in actual practice. The non-occurrence of these difficulties is explained by the fact that in-situ combustion fronts are often not truly vertical. In actuality, field tests show that combustion fronts generally advance more rapidly at the top of a producing formation than they do at the bottom. Specifically, after a combustion front has been initiated and has advanced away from an injection well it assumes a sloping configuration having its lower edge

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closest to the injection well and near the bottom of the formation and its upper edge extending downstream from the lower edge into a position near the upper extremity of the producing formation. As so formed, the combustion front eventually assumes a position wherein its surface near the upper edge is nearly horizontal. This position is explained by the difference in density between the combustion-supporting injected gas and the formation liquids and also by the gas cap that is frequently present in hydrocarbon-producing formations. As a result, the front assumes a position wherein it lays over a region of the producing formation far exceeding the region that is contacted by a vertical combustion front. Thus, after a given period, the area of the producing formation heated by the sloping combustion front is much larger than would be the case with a vertical front and the heated zone extends much closer to the production well. Due to the increased area of the combustion front, the temperature of the producing formation heated thereby is not as high as the temperature that would be attained by a vertical combustion front. The latter characteristic is advantageous since a sloping combustion front of a moderate temperature (e.g., 700° F. or less) is more efficient in reducing viscosity of hydrocarbons within a producing formation than is a vertical combustion front of extremely high temperature. Furthermore, heating a producing formation over an extended nearly horizontal area has the advantage that a viscous bank of hydrocarbons is unlikely to build up downstream of the combustion front to result in the prevention of fluid flow through the formation. It is noted that with an inclined combustion front the hydrocarbons reduced in viscosity by the heat of combustion tend to gravitate downwardly within the producing formation and are forced horizontally therethrough by injected combustion supporting gas.

The use of an inclined or sloping combustion front for secondary recovery, however, results in the formation of a burned zone between the injection well and surrounding producing wells at the upper portion of the producing formation before combustion has advanced through the lower portion of the producing formation. When a burned zone is established between injection and production wells, the pressure drop between the wells is appreciably reduced, where the gas is injected at a substantially constant rate, and thus the effect of the pressure drive is lessened. The reduced pressure drop has the advantage that injection pressure requirements will be lower and accordingly, compression costs will be lessened. Furthermore, it is noted that the use of an inclined combustion front utilizes gravity as a driving means and thus reduces the amount of pressure drive required for production.

When the upper edge of an inclined combustion front has reached a production well, portions of the injected combustion-supporting gas can pass between the wells through the burned zone without reacting, as desired, at the combustion front. Where both gaseous and liquid fluids are being produced from the production well, the unreacted combustion supporting gas is also produced. The production of unreacted combustion-supporting gas from the production well is undesirable because the gas is ineffectively utilized and thus excessive amounts of combustion-supporting gas must be injected to support the desired combustion front. Furthermore, any unreacted combustion-supporting gas in the form of oxygen in the effluent gas produced from the production well can lead to damaging in-the-well reactions with the hot crude produced from the well. Specifically, these reactions damage the well by creating high temperatures therein which reduce the strength of the tubular operating components of the well. Furthermore, such reactions within the well may also result in objectionable deposits within

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the well (e.g., coke) which tend to restrict the operation thereof.

It is, therefore, a prime object of the present invention to provide a process of effectively using an inclined in-situ combustion front for the secondary recovery of hydrocarbons. With respect to this object it is another object of this invention to utilize an inclined combustion front while avoiding the above-enumerated problems previously encountered with such combustion fronts.

Another object of the invention is to provide an in-situ combustion secondary recovery process wherein the heat created by in-situ combustion is effectively and efficiently utilized.

A further object of the invention is to provide an in-situ combustion secondary recovery process wherein both the pressure of combustion-supporting gas injected into a producing formation and the gravitational effects within the formation are utilized to drive liquid hydrocarbons towards a producing well. In this respect it is another object of the invention to provide an in-situ combustion secondary recovery process wherein injection pressure requirements are minimized.

Yet another object of the invention is to provide an in-situ combustion secondary recovery process wherein reactions between oxygen and hydrocarbons within the producing well are avoided. With respect to the latter object, it is a more specific object of the present invention to provide an in-situ combustion secondary recovery process wherein gases and liquids are separately produced in controlled ratios.

Broadly, the present invention provides a process for the recovery of viscous hydrocarbons within a hydrocarbon bearing formation. To commence the process, a gas injection well is completed into the hydrocarbon bearing formation and at least two production wells are also completed into the formation at different distances downstream from the injection well. Upon completing the wells, the production wells are provided with means for separating and separately producing the gases and liquids that flow into the wells. After the wells are completed and equipped, underground combustion is initiated in the hydrocarbon bearing formation immediately surrounding the injection well and a combustion front is advanced from the injection well by injecting combustion-supporting gas therethrough and into the hydrocarbon-bearing formation at a rate at which the upper edge of the combustion front will reach the production wells before the lower edge. During the initiation and advance of the combustion front, fluids are produced from a production well nearest to the injection well and the gaseous fluids so produced are analyzed to detect the presence of unreacted combustion-supporting gas. When unreacted combustion-supporting gas is detected in the gas produced from the well nearest to the injection well, the production of gaseous fluids from this well is restricted while production of liquid fluids is continued with minimum restriction. At this point, fluids are produced from the production wells located further downstream from the injection well and the production from each of these wells is controlled in a manner corresponding to the above-described analyzing and restricting of the production of gaseous fluids from the well nearest to the injection well. Naturally, when the production well spaced from the injection well by the maximum downstream distance within the confines of the reservoir has been reached, the production cannot be so controlled since there are no alternative wells from which to produce gas. It is noted that the production of gas is necessary in order to facilitate the injection of combustion-supporting gas and thus support the desired combustion front.

The enumerated and other objects of the invention and the details of the process will become more apparent when viewed in light of the following description and accompanying illustrations, wherein:

FIGURE 1 diagrammatically illustrates a vertical sec-

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tion of a hydrocarbon-bearing formation having injection and production wells completed therein to facilitate the process of the present invention;

FIGURE 2 diagrammatically illustrates a plan view of an injection and production well arrangement adapted to be used with the process of the present invention;

FIGURE 3 illustrates a detailed vertical section of a producing well containing one form of means for separating and separably producing gases and liquids in accordance with the process of the present invention; and,

FIGURE 4 diagrammatically illustrates a vertical section of a hydrocarbon-bearing formation penetrated by injection and producing wells and having the process of the present invention applied thereto.

Referring now to FIGURE 1, therein is illustrated a hydrocarbon-bearing formation or reservoir in diagrammatic vertical section prepared for secondary recovery according to the process of the present invention. In this figure, the numeral 10 designates the permeable hydrocarbon-bearing formation having relatively impermeable formations 11 and 12 defining its upper and lower extremities, respectively. An injection well 13 is formed from the surface of the earth into the producing formation 10 wherein it is lined with a perforated liner. It is to be understood that the injection well 13 could possibly be formed without a liner or casing string where the formations through which it extends are sufficiently consolidated and that injection need not be into the entire formation interval. In addition to the injection well, production wells 14, 15 and 16 are formed from the surface of the earth into the producing formation 10. As illustrated, the production wells extend slightly below the producing formation and are lined with casing strings provided with perforations in the close proximity of the upper and lower extremities of the producing formation.

The production wells 14, 15 and 16 are located at increasing distances downstream from the injection well 13. Each of the production wells 14, 15 and 16 have extending therethrough production strings 17, 18 and 19, respectively. It is noted that the production strings extend through the casing strings of the production wells to a level below the lower extremity of the producing formation 10. Through the latter arrangement, the open lower ends of the production strings are positioned to produce liquids which accumulate in the area of the production wells extending below the producing formation. The lower perforations in the casing strings of each of the production wells permit liquid hydrocarbons driven through the producing formation by pressure and gravity forces to enter the production wells and accumulate at the lower ends thereof where they may be produced through means of the production strings. The perforations at the upper ends of the casing strings in each of the production wells provide means whereby gases may enter the production wells and be produced therefrom. From the arrangement of the casing string and production string in each of the production wells, it is believed apparent that they provide means for separating and separably producing gases and liquids. A more detailed description of the operation and structure of the production wells will be developed subsequently with respect to FIGURE 3.

The perforated liner in the injection well 13 provides means whereby combustion-supporting oxygen-containing fluids may be introduced into the producing formation 10 to initiate and sustain combustion therein. Typically, combustion is initiated by injecting air into the well 13 until hydrocarbon in the formation immediately therearound are oxidized and heated to the point of ignition. It is to be understood, however, that combustion may also be initiated by other means conventional in the art, such as a downhole heater. After combustion is initiated, combustion-supporting fluid, such as the air utilized to initiate combustion, is continuously injected into the well 13 to support combustion within the producing forma-

tion 10. Upon the maintenance of a combustion front, the front assumes a sloped configuration as indicated by the line 22. It is to be understood that the exact configuration of the front varies with time and that the line 22 illustrated in FIGURE 1 designates a combustion front as established after a considerable period of combustion. Furthermore, as indicated to the left and right of the injection well 13, the combustion front extends in arcs around the injection well in the regions in which the injected combustion-supporting gases are moving away from the well.

It is noted that the combustion front indicated by the line 22 is of sloped configuration and assumes position approaching horizontal at the upper edge. The combustion front configuration indicated by the line 22 is typical of a configuration that can be attained when utilizing a combustion front for secondary recovery purposes. With this configuration, the combustion zone is said to lay over the hydrocarbon-bearing formation desired to be produced. Observations indicate that the degree of layover seems to be inversely proportional to the ratio of gravity to applied forces on the hydrocarbons within the formation. More specifically, the average slope of the combustion surface is directly proportional to the injection rate and inversely proportional to the formation thickness, the well spacing, and the formation permeability. Of the latter factors, the operator of a secondary recovery process for a particular project can only control the injection rate and the well spacing. Therefore, within certain limits, the operator of a secondary recovery process can control the amount of layover. Variations in the injection rate are limited on the upper extremity by the allowed injection pressure and on the lower extremity by the rate of return on the investment. Variations on the well spacing are dictated primarily by economics and the area of the producing formation being treated. The present invention, as will be developed in greater detail subsequently, is intended to utilize a sloping combustion front to efficiently and effectively recover viscous hydrocarbons. Therefore, both the injection rates and the well spacings are controlled to extend combustion zone layover approximately as illustrated in FIGURE 1.

Referring now to FIGURE 2, therein is illustrated a diagrammatic plan view of an injection and production well arrangement, a portion of which is illustrated in FIGURE 1. The arrangement of FIGURE 2 is merely intended to be exemplary of a complete arrangement that could be used with injection and producing wells as located in FIGURE 1. The three lines of wells having the wells 14, 15 and 16 therein corresponding to the production wells illustrated in FIGURE 1 are located at increasing distances from the line of injection wells 13. The wells 14a, 15a and 16a correspond to the wells 14, 15 and 16, respectively, in their construction and spacing from the injection wells. The flow pattern attainable in a generally flat homogeneous reservoir formation is indicated by the arrows. A plan view of the inclined combustion front would be positioned between the lines illustrating the upper and lower edges of the front.

In a sloping reservoir it would be preferable to complete the line of injection wells corresponding to the wells 13 near the upper edge of the reservoir and to advance the drive down dip within the formation. In advancing the drive an additional row of producing wells (e.g., downstream of a row having wells corresponding to the wells 16 therein) is placed on production and, when production becomes uneconomical from the producing wells in a row having wells corresponding to the wells 15 these wells are connected as injection wells while the wells in a row having wells corresponding to the wells 13 therein are shut in to maintain the pressure within the formation. In producing from a small generally circular reservoir, or in a pilot operation, it may be desirable to employ a single central injection well surrounded by a plurality of produc-

tion wells at different distances downstream of the flow, which would comprise a generally radial flow.

FIGURE 3 illustrates a detailed vertical section of the production well 14 illustrated in FIGURES 1 and 2. It is to be understood that the well 14 was chosen for purposes of illustration only and that the structure of the other production wells would correspond to the well 14 in that each would contain a means for separating and separately producing gaseous and liquid fluids. It is noted that such a separation need not be quantitative but should isolate the bulk of the liquid fluids from those that are gases at the ambient conditions of pressure and temperature. The numeral 23 of FIGURE 3 designates a casing string extending into the well 14, through the producing formation 10 and slightly into the relatively impermeable formation 12. The casing string is provided with upper and lower perforations 24 and 25, respectively, to communicate with the interior of the well with the producing formation therearound. Through these perforations, gases pass into the casing string and rise upwardly while liquids pass into the casing string and settle into the reservoir formed by lower end thereof extending into the formation 12. Where desirable, the loss of liquid into formation 12 can be prevented by casing off the wall and plugging the bottom of the portion of the borehole that extends within formation 12. The arrows extending from the perforations indicate the direction of flow of the fluids passing therethrough. Fluids which accumulate in the reservoir formed by the lower end of the borehole are removed therefrom and to the surface of the earth by the production string 17. This removal is facilitated by a pump 26 received in the production string and a sucker rod 27 secured thereto. FIGURE 3 also illustrates a string 28 to be used for running thermocouples into the well. Through the latter provision, the temperature of the well can be continuously monitored.

With the information obtained by monitoring the well temperature, the temperature of the well may be controlled by either introducing a heat absorbent, such as water, into the well, or by controlling the gas-to-oil ratio of hydrocarbons produced from the well. Control of well temperature by the introduction of a heat absorbent would generally be affected by introducing the absorbent into the annulus between the casing string 23 and the production string 17. This introduction could be carried out at the surface of the earth through any of the means well known to those skilled in the well completion and production art. Droplets 29 indicate a flow of liquid heat absorbent into the well. In a typical situation a flow in the order of 50 barrels of water per day might be used, but actual rates would be dictated by economics and requirements to keep the well under control (temperature wise). Temperature control through control of the gas-to-oil ratio of fluids produced from the well would typically be effected by surface control means as are well known in the oil well production art. The latter type of control is particularly suitable for the present invention, since the wells thereof are designed to facilitate the separate production of gaseous and liquid fluids. Specifically, with the arrangement of FIGURE 3 liquid fluids would be removed through the production string 17 while gaseous fluids would be removed through the annulus between the casing string 23 and the production string 17.

Referring now to FIGURE 4, therein is illustrated a schematic vertical section corresponding substantially to FIGURE 1 and showing the behavior of a combustion front around a production well during the production of gas therefrom. The solid line 22 of FIGURE 4 designates a combustion front correspondingly identically to that of FIGURE 1 which results from substantially completely restricting the gas production from the production well 14. The dashed line 22a designates the combustion front created when gas is produced from the production well 14. The increased combustion front around the production well results from the convergence of gas

flow lines into the producing well which, in turn, promotes active combustion therearound. The increased combustion around the production well results in the attainment of higher temperatures near the production well which, if controlled, function to increase the productivity of the well. It is noted that in situations where the gas flux around the production well is very high, the active combustion front created around the well may actually be separated from the combustion front designated by the line 22. In the latter case, the combustion front would vary in appearance from that designated by the line 22a, although its effect would be substantially the same.

In applying the process of the present invention, injection and production wells are first completed into the producing formation desired to be produced as illustrated in FIGURE 1. It is noted that the application is not necessarily limited to the injection and production well arrangement illustrated in the aforescribed figures. Specifically, any number of injection wells might be used and the production wells may be arranged along irregular lines. Each of the production wells is equipped with means for separating and separately producing gas and liquid and each is preferably equipped with thermocouples, for example, as carried by a string 28 as illustrated in FIGURE 3. Thus, the production wells are facilitated for separating and separately producing gases and liquids and for monitoring well temperature.

After the injection and production wells are completed, as illustrated in FIGURES 1 and 2, combustion is initiated in the area of the producing formation immediately surrounding injection wells 13. Typically, the combustion is initiated by introducing oxygen into the formation through the injection well to oxidize hydrocarbons within the producing formation to raise their temperature to the ignition point. Once combustion is indicated, the injection of an oxygen-containing combustion-supporting fluid into the producing formation is continued to support the desired combustion front. The spacing of the production wells 14, 15 and 16 and the rate of injection of the combustion-supporting fluid is selected to enhance the attainment of the desired inclined or sloping combustion front, as illustrated in FIGURE 1. The exact rate at which the combustion-supporting fluid is injected is determined experimentally to maximize the effect of gravity on the fluids forced through the reservoir formation.

Upon initiating combustion around the injection wells 13, gaseous and liquid fluids are produced from the production wells 14. Although hydrocarbon production may begin immediately upon the initiation of the combustion front around the injection well, it is recognized that there may be some delay in time before significant amounts of hydrocarbons appear in the well. At this point it is noted that with an arrangement as illustrated in FIGURE 2, initial production would not be limited to the wells 14, but rather would be carried out in each of the production wells that are close enough to the injection wells 13 to be influenced by the flow of fluids injected therethrough, such as the wells 14a. The obvious reason for the latter production sequence is that the combustion front tends to advance radially in all directions from the injection wells 13, but moves most rapidly into the regions exhibiting the least resistance to flow.

Attention is now directed to the line 22 of FIGURE 1 and the combustion front indicated thereby. The line 22 is not intended to illustrate the combustion front in the early stages of this formation, but rather shows the combustion front after it has advanced beyond production wells 14 by a considerable distance. As the combustion front indicated by the line 22 advances through the producing formation 10, the gases and liquids producing from each of the production wells are separated and separately produced. In addition, the gases produced from each of the wells are analyzed to detect any unreacted oxygen therein. The presence of any appreciable amount of unreacted oxygen in the gas produced from a particular pro-

duction well indicates that the combustion front has advanced up to or past the production well and that injected gas is passing through the burned zone and between the injection well and the production well without reacting with hydrocarbons. For example, in the FIGURE 1 example at least some injected oxygen would pass through the burned out zone between the injection well 13 and the producing well 14 without reacting to produce combustion. In FIGURE 1, it is also possible that an appreciable amount of unreacted gas might also pass to the producing well 15 without reacting.

Upon the detection of unreacted combustion-supporting gas in the gaseous effluent produced from a particular well, the production of gas from that well is restricted and gas is produced from the production well or wells next encountered along the direction of the flow within the reservoir formation. Generally, gas production is restricted in the production wells to the degree necessary to prevent the temperature therein from exceeding 700° F. The purpose of producing gas in this manner is to utilize the combustion-supporting gas with maximum efficiency and also to avoid reaction between hydrocarbons and unreacted oxygen within the producing wells. The latter reactions are objectionable because they function to generate heat which may damage the structure of the well and detrimentally affect produced hydrocarbons. At this point it is noted that gases produced with the process of the present invention are generally successively produced only from production wells spaced from the adjacent well by successively increasing distances. However, the production of liquid hydrocarbons from the production wells spaced from the injection wells by varying distances does not necessarily need to be successive, but rather all wells may be produced simultaneously if this appears practical in actual application. Similarly, some, but restricted, gas production may be continued from the wells first reached by the combustion front. Some gases of course will be dissolved in the oil produced from the production well and therefore will be produced as long as oil is drawn from the well. However, when unreacted combustion supporting gas is detected in the effluent from the producing wells the gas flow in such a production well must be restricted to maintain the temperature in that well at or below 700° F. in order to prevent serious damage to the well structure.

After the production of gas from production wells 14 and 14a has been restricted, gas production from the wells 15 and 15a is commenced in a manner corresponding to that initially carried out on the wells 14 and 14a. Naturally, production wells spaced downstream from the injection wells 13 by a distance corresponding to that of the wells 15, such as the wells 15a, are also produced in a manner identical to that of the wells 15. The gaseous production from the wells 15 and other similarly spaced wells is monitored, as was the gaseous production of the wells 14, to detect the presence of unreacted oxygen therein. Once such unreacted oxygen is detected, the production of gas from the wells 15 and other similarly located wells is restricted in a manner identical to that practiced on the wells 14 and 14a and gaseous production is commenced on the next successively spaced well from the injection wells 13, namely, the wells 16 and any other wells spaced from the injection well by a distance corresponding to that of the wells 16, such as the wells 16a. In this manner, the combustion front is advanced from the injection well and through the producing formation while the combustion-supporting gas is efficiently utilized without producing undesired reactions within the producing well. It is noted, however, that when the combustion front reaches the outermost of the successively produced wells, the production of unreacted oxygen-containing combustion-supporting fluids is unavoidable. This situation results from the fact that it is desirable, if not absolutely necessary, to produce some gas from the formation at all times in order to facilitate the injection of the combustion-supporting gas through the injection well.

In addition to controlling the production of gas from the successively produced production wells to avoid the production of unreacted oxygen, the control of such gas production may also be affected to initiate secondary combustion front around successively produced wells, as illustrated by the line 22a in FIGURE 4. Such secondary combustion front may be initiated by producing just enough gas from the well to increase the gas flux therearound. The creation for such combustion fronts is often desirable since it increases the temperature of the formation immediately around a production well and thus reduces the viscosity of hydrocarbons therearound and facilitates their production from the well.

Temperatures around a production well should not be excessive if the most efficient utilization of combustion-supporting gases is to be obtained. Specifically, it has been found desirable to limit the temperature of a producing well to 700° F. or less. The exact temperature of a particular well can be monitored and detected through means of a thermocouple carrying line 28 communicating with a temperature-indicating device on the surface of the earth. The information obtained from such an indicating device is utilized to determine when steps, as were developed previously, should be taken to control the temperature of a producing well.

To summarize, the present invention provides a process wherein a sloping or inclined in-situ combustion front is used to facilitate effectively and efficiently the secondary recovery of hydrocarbons. The use of the inclined combustion front is advantageous since it increases the surface area of the combustion front and increases the rapidity with which heat is applied to portions of the formation near the producing wells. Control of the combustion front is effected by selecting optimum well patterns and combustion-supporting fluid injection rates. When the combustion front of the process encounters a production well, the undesirable production of unreacted combustion-supporting gases is prevented by separating these gases and controlling the rate at which they are produced. In addition to promoting the efficient use of combustion supporting gases, the controlled production of such gases is also desirable since it avoids reactions between oxygen and hydrocarbons within the well and also affects temperature control within the well. Temperature control of the well can also be affected by introducing a heat absorbent, such as water, thereinto.

In conclusion, it is noted that the present invention is not intended to be limited to the specific embodiment illustrated and described. For example, the invention may be practiced with a greater or lesser number of production wells, the only requirement being that the production wells be controlled in the manner exemplified by the foregoing detailed description. Furthermore, the exact pattern of the production wells may be varied as long as wells to be successively produced are spaced from the injection well or wells by varying distances. Therefore, various changes in the details of the described process may be made, within the scope of the appended claims, without departing from the spirit of the invention.

I claim as my invention:

1. A process for the secondary recovery of hydrocarbons, comprising the steps of:
  - (a) completing a gas injection well into a relatively permeable hydrocarbon-bearing formation;
  - (b) completing a production well into the hydrocarbon-bearing formation at a spaced location with respect to the injection well;
  - (c) providing the production well with means for separating any separately producing gases and liquids;
  - (d) initiating underground combustion in the hydrocarbon-bearing formation immediately surrounding

the injection well and advancing the combustion front therefrom by injecting combustion-supporting gas into the injection well at a rate at which the upper edge of the combustion front reaches the production well before the lower edge;

- (e) producing fluids from said production well and analyzing the gas so produced to detect the presence of unreacted combustion-supporting gas therein; and,
  - (f) restricting production of gas from said production well when unreacted combustion-supporting gas is detected therein sufficiently to prevent the temperature from exceeding 700° F. in said production well while continuing to produce liquid effluent therefrom.
2. A process according to claim 1 wherein; a plurality of injection wells are completed and the injection and production wells are arranged along relatively straight parallel lines to effect a line drive within the hydrocarbon-bearing formation.
  3. A method for improving the recovery of hydrocarbons from oil-bearing reservoirs by controlling the in-situ combustion therein, comprising:
    - (a) completing at least one injection gas well into a relatively permeable hydrocarbon-bearing formation;
    - (b) completing a plurality of production wells in said permeable hydrocarbon-bearing formation at spaced locations from said injection well, said production wells being located at different downstream distances with respect to said injection well;
    - (c) providing said production wells with means for separating and separately producing gases and liquids from said production wells;
    - (d) initiating underground combustion in the hydrocarbon-bearing formation immediately surrounding said injection well and advancing a combustion front therefrom by injecting combustion-supporting gas into injection well at a rate which the upper edge of said combustion front reaches said production wells before the lower edge;
    - (e) producing fluids from said production wells and analyzing the gaseous fluids so produced to detect unreacted combustion-supporting gas therein;
    - (f) restricting the production of said gaseous fluids from any said production well when unreacted combustion-supporting gas is detected therein sufficient to prevent the temperature therein from exceeding 700° F. while maintaining the production of liquid effluent from said production well; and,
    - (g) successively producing fluids from said production wells at increased downstream distances from said injection well until unreacted combustion-supporting gas is detected therein and then restricting the production of gaseous fluids therefrom sufficient to prevent the temperature therein from exceeding 700° F.

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